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Weilin Hou, A. Kanaev, Sarah Woods

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It is a well-known fact that the major degradation source on EO imaging underwater is from scattering by the medium itself and the constituents within, namely particles of various origins and sizes. Recent research indicates that under certain conditions, such degradations could be caused mainly by the variations of index of refraction associated with temperature and salinity micro-structures in the ocean. These would inherently effect the optical signal transmission underwater, which is of vital interest to both civilian and military applications, as they could include diver visibility, search and rescue, mine detection and identification, and optical communication. The impacts from the optical turbulence are yet fully understood, in part due to the challenges associated with parameterization of individual factors. This study presents the initial attempts in quantifying the level of EO image degradation due to optical turbulence in natural waters, in terms of modulation transfer functions, and enhancements using the lucky patch approaches derived from optical flow techniques. Image data collected from natural environments during SOTEX (Skaneateles Optical Turbulence Exercise, July 22-31, 2010) using the Image Measurement Assembly for Subsurface Turbulence (IMAST) are presented. Optical properties of the water column were measured using WETLab's ac-9 and LISST (Laser In Situ Scattering and Transmissiometry), in coordination with temperature, conductivity and depth. Turbulence conditions were measured by two different approaches, namely a 3D Doppler based velocimeter with Conductivity/Temperature combo, and a shear based Vertical Microstructure Profiler.

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# Assessing EO image degradation from underwater optical turbulence in natural waters

Weilin (Will) Hou[1], Andrey Kanaev[2], Sarah Woods[1,3]
1 Oceanography Div., Naval Research Lab, Stennis Space Center, MS
2 Optical Sciences Div., Naval Research Lab, Washington DC
3 NRL ASEE Postdoc Fellow

## ABSTRACT

It is a well-known fact that the major degradation source on EO imaging underwater is from scattering by the medium itself and the constituents within, namely particles of various origins and sizes. Recent research indicates that under certain conditions, such degradations could be caused mainly by the variations of index of refraction associated with temperature and salinity micro-structures in the ocean. These would inherently affect the optical signal transmission underwater, which is of vital interest to both civilian and military applications, as they could include diver visibility, search and rescue, mine detection and identification, and optical communication. The impacts from the optical turbulence are yet fully understood, in part due to the challenges associated with parameterization of individual factors. This study presents the initial attempts in quantifying the level of EO image degradation due to optical turbulence in natural waters, in terms of modulation transfer functions, and enhancements using the lucky patch approaches derived from optical flow techniques. Image data collected from natural environments during SOTEX (Skaneateles Optical Turbulence Exercise, July 22-31, 2010) using the Image Measurement Assembly for Subsurface Turbulence (IMAST) are presented. Optical properties of the water column were measured using WETLab's ac-9 and LISST (Laser In Situ Scattering and Transmissiometry), in coordination with temperature, conductivity and depth. Turbulence conditions were measured by two different approaches, namely a 3D Doppler based velocimeter with Conductivity/Temperature combo, and a shear based Vertical Microstructure Profiler.

## 1. INTRODUCTION

The amount of image degradation in the underwater environment is a function of optical properties of the water. The cause of the degradation has been mostly attributed to the dirt, or inorganic as well as organic particles in the water and it is rightly so. Most research has been focusing on reducing the impact of particle scattering by means of discriminating scattering photos involving polarization, range gating, modulation, and by means of restoration via deconvolution [1-6]. However, in clean oceanic or lake waters, another factor could come into play. This is the scattering by optical turbulence, which is the result of the variations of the index of refraction of the medium. This is mostly associated with the turbulence structures of the medium, or water body in our case. Degradation of the image quality in a scattering medium involving turbulence has been studied mostly in atmosphere. These studies are mainly focused on modeling the optical transfer function, in an effort to restore the images obtained, such as in air reconnaissance or astronomy studies [7, 8]. Little has been done regarding the turbulence effects on imaging formation in water, mainly due to the dominant particle scattering and strong attenuation associated, as well as challenges in providing a stable platform and quantifying the level of turbulence. It has been commonly observed that visibility can quickly reduce to zero in a few meters, or even a few feet in coastal waters, especially those inside a harbor, or estuarine areas like Mississippi. The same applies to regions of strong re-suspension from the bottom, both in coastal regions as well as in the deep sea. However, the effects of turbulence have been postulated to have impacts over long image transmission ranges [9], which has been supported by light scattering measurements and simulations [10]. Under extreme conditions, observations have been made that involve target ranges within a few feet [11]. The images obtained under such conditions are often severely degraded or blurred, on par with or more than those caused by particle scattering. Overcoming such challenges to increase both the reach and the resolution is of vital importance to military and civilian applications, from mine detection and identification, to diver visibility, undersea communication, and search and rescue operations. It is important to establish a good understanding of the

limiting factors under different conditions. The SUIM model [12] was developed to address this issue and it has been shown that on average, the relative contribution of different components [3, 13] in underwater imaging applications can be expressed in terms of the optical transfer function (OTF) as dot products of each component. A turbulence intensity parameter ($S_n$) is used to describe the optical turbulence intensity that is dependent on the structure function, which can be further expressed in terms of the turbulence dissipation rate of temperature, salinity and kinetic energy, assuming Kolmogorov power spectrum type. Here we present the results of a recent field exercise and efforts associated with the model validation. Since the phase information can be ignored under incoherent imaging conditions, the magnitude of the OTF or the modulation transfer function (MTF) will be used interchangeably here. A new restoration algorithm was developed and applied to the turbulence degraded images to compensate for the impact of turbulence.

## 2. SOTEX EXPERIMENT

Skaneateles Optical Turbulence Exercise (SOTEX) was carried out from July 22-31 2010 in one of the finger lakes in upstate New York, aimed to examine the above mentioned impacts in the field. Optical turbulence underwater is primarily a function of temperature structure, although salinity variations could, at times, contribute to strong optical turbulence [11]. Intensified thermoclines in natural environments provide a convenient setup to examine this chaotic process. Details of SOTEX can be found in previous publications [14, 15]. For convenience, the key elements are briefly outlined here. Data were obtained during a multi-day exercise at two different locations. The deeper one is near the center of the lake (42.8668° N, 76.3920° W) over a sloping bottom with an approximate depth of 70 m, while the shallow station is at the northern end of the lake (42.9063° N, 76.4058° W) over a flatter bottom with an approximate depth of 50 m. We'll be using data primarily from the former (deeper) location. Skaneateles was chosen for this exercise on account of its well-known optically clean waters, having the highest clarity of any of the Finger Lakes, with an average Secchi depth near 8 m (Effler et al. 2007), thus allowing for imaging under varied turbulent strength, but with little scattering contribution from particulates. Nonetheless, a particle layer was present right below a strong turbulence layer. Only images above this layer will be used for the present study.
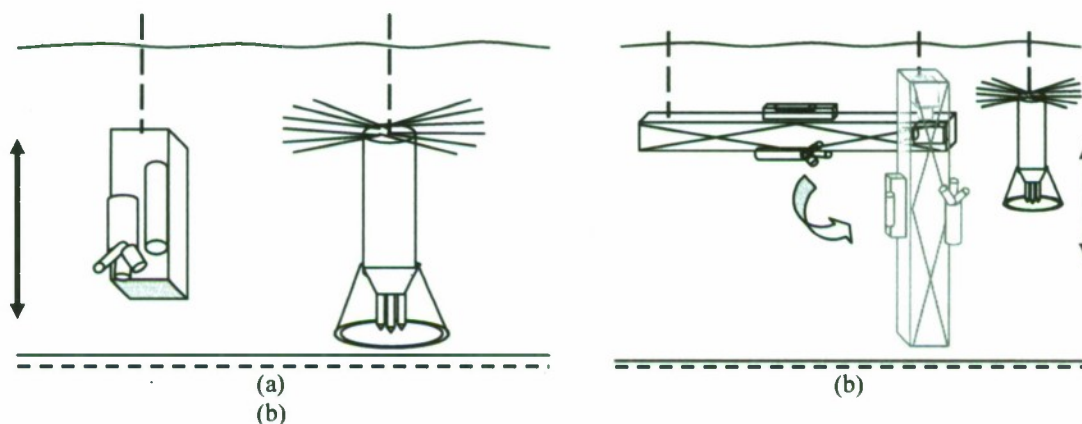


**Figure 1.** Diagram of deployment setup showing alternate deployment configurations: (a) Vector/CT deployed vertically on optics package, and (b) Vector/CT deployed on lMAST both vertically and horizontally. Note, in both instances, the VMP was deployed from a separate vessel.

In order to quantify the level of image degradation due to optical turbulence, it is imperative to accurately measure the physical conditions from which such impacts arise. For this purpose, we used two different approaches for turbulence measurements, namely a Vertical Microstructure Profiler (VMP) and a Vector Velocimeter combined with a Conductivity and Temperature sensor (Vector/CT) [15]. We inter-calibrated the two systems at the onset of

the exercise, by deploying the Vector/CT from the optics package, while the VMP was deployed from a separate vessel nearby, as depicted in Figure 1a. While the Vector/CT profile consisted of pauses at particular depths for acquiring a time series of velocities that would be used for turbulence calculations, the VMP profiled continuously. For quantifying impacts of optical turbulence on image degradation, the Vector/CT was deployed upon a rigid structure, the IMAST (Image Measurement Assembly for Subsurface Turbulence), a 5m long structure used for acquiring images [14, 15]. The IMAST was deployed both vertically and horizontally, as depicted in Figure 1b, both during the day with a passive imaging target and at night with an active target made of an iPad®, and also profiled the water column in a step fashion, pausing at each depth for a given period of time to acquire images and velocity time series at a given depth. The VMP was deployed from a separate vessel, and profiled continuously during the IMAST deployment and the two turbulence measurement results agreed in most cases [15]. Complementary profiles of the water column optical properties were also obtained with an ac-9, CTD, and Laser In-Situ Scattering Transmissometer (LISST) for estimating both particle size distributions and the volume scattering function of the water.



**Figure 2**. IMAST night deployment configuration: imaging camera and housing (left end of the frame); active target made out of iPad (right end of the frame); details on other sensors including Vector refer to text.

## 3. DATA PROCESSING AND RESULTS

Standard (USAF-1951) and custom-made resolution charts are used, with different spatial frequencies for quick examination of the image degradation. A pair of sample images is shown in Figure 3. They were taken at two different depths, one at 2.8m, which is essentially free of optical turbulence, while the one at 8.7m is strongly influenced by optical turbulence [14, 15]. Both are taken under the horizontal deployment configuration. One can notice that despite the similarity of the measured optical properties in beam attenuation at 532nm (Fig.4), the image inside the strong turbulence layer (right) suffered much more degradation, compared to the weaker turbulence situation (left). The turbulence dissipation rate ranged from very low values up to $10^{-6}$ $m^2s^{-3}$ at the highest for kinetic energy, and $10^{-5}$ $^{O}C^2/s$ for temperature (Fig.5). These two images are obtained from the same path length, camera setting and target intensity level. Thus the major contributing factor is the optical turbulence, as shown in Figure 5. Details of the measurements and data processing can be found in the reference [15].
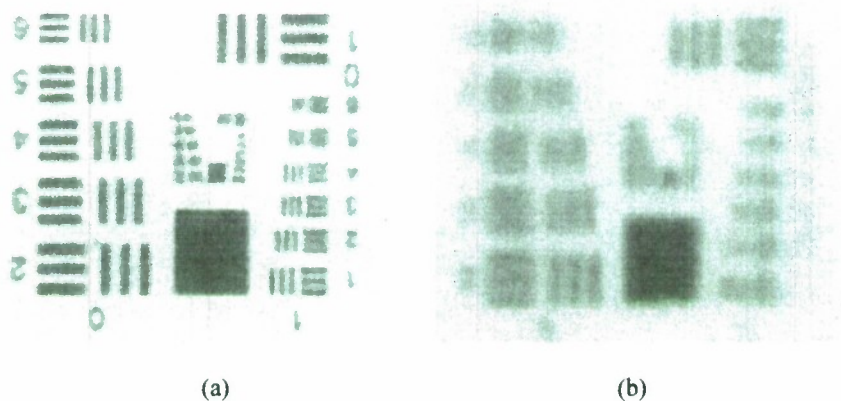
(a)                       (b)

**Figure 3.** Sample image pair obtained by IMAST during night deployment (horizontal) of July 27. The corresponding conditions can be seen in Fig. 4. The left was taken at 2.7m depth, while the right was from 8.7m, under same path, camera and light settings.
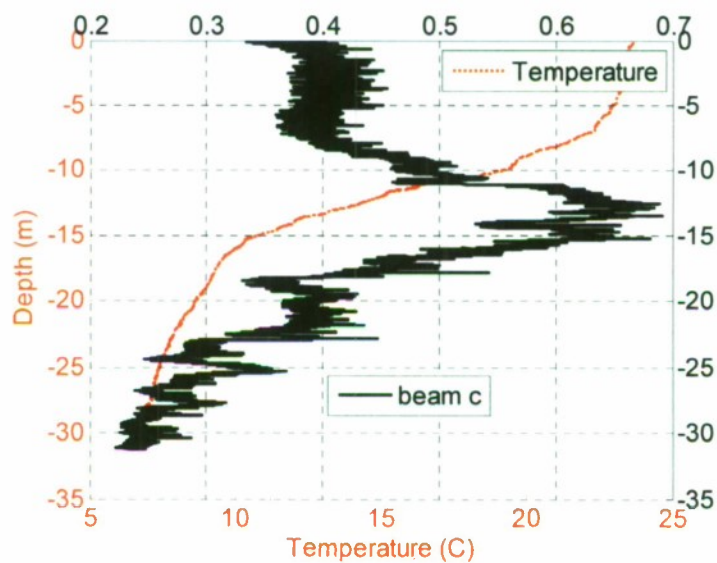


**Figure 4.** Optical properties (beam-c at 532nm) and temperature profile measured during July 27 night IMAST deployment.
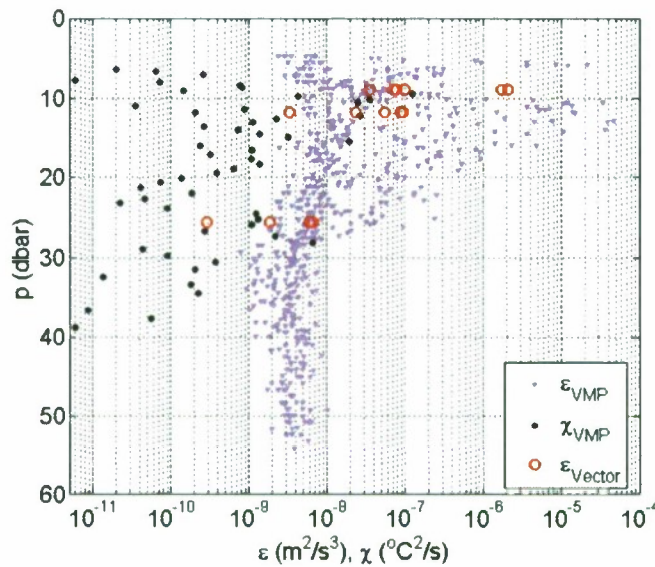
**Figure 5.** Profiles of turbulent kinetic energy dissipation rates, $\varepsilon$ (m$^2$s$^{-3}$) determined from VMP (blue triangle) and Vector (red open circle) measurements, and thermal dissipation rates, $\chi$ ($^\circ$C$^2$s$^{-1}$) determined from VMP (black dot) for July 27 day time deployments. The structures maintained similar strengths into the night deployment time frame.

One can clearly see from Fig. 3 that the level of degradation is different for these images obtained at different depths, which correspond to different turbulence conditions. To the first order, we can quantify the level of the image degradation in terms of the MTF, which describes the total system response at different spatial frequencies. Granted, this might not be the best approach for turbulence degraded images, especially under high levels of distortion. However, we intend to estimate the long exposure (averaged) impacts, and such an approach is acceptable for this first order calculation. There are numerous methods to derive the MTF from a given image. We adopted the standard slant edge technique [16, 17], using different portions of the image. The results are shown in Figure 6 (a-d). These are obtained from an active source (one way path) during the nighttime deployment of July 27, to minimize path radiance. Fig. 6a shows the averaged MTF at the shallower depth (2.8m), compared to several cases (sequences, denoted A, B and C) at the deeper depth where optical turbulence is strong. For each of the image sequences at 8.7m, the MTFs are estimated using the same region of interest (ROI) of consecutive frames, over 10-frames for long exposure, to be compared to single (a, b, c) and averaged results at 2.8m, as well as modeled outcome at 8.7m. The averaging and comparison at 2.8m is used to examine the level of degradation over longer exposure. The SUIM model [12, 14] is used to incorporate the impacts of optical turbulence at 8.7m, using different turbulence parameters. It is worth noting that the signal to noise ratio (SNR) cannot be improved when multiple frames are used, as each individual frame would typically undergo a different amount of degradation. Therefore the averaging would only increase the SNR towards the low frequency elements, and leave behind random variations at the high frequency end. This is necessary, however, in order to contain all of the variations caused by the optical turbulence [12].

Details of the SUIM model and application can be found in previous publications. The results shown in Figs 6b-6d suggest that indeed the model can be used to assess the level of impact of optical turbulence on image degradation underwater, when the assumption can be made that the difference in MTFs at the different depths is primarily the result of turbulence structure. By applying kinetic energy dissipation rates of $10^{-7}$~$10^{-9}$ m$^2$s$^{-3}$, and temperature dissipation rates of $10^{-6}$~$10^{-8}$ $^\circ$C$^2$/s, one can see that the model result approximates the field measurements reasonably well. The differences between the model and measurements could be a result of myriad factors. The primary reason is likely the difference in measurement scales in the temporal domain. This is troublesome, especially when spatial fluctuations of the turbulent flow cannot be treated as isotropic and statistically homogenous. More rigorous post-processing of images involving multiple ROIs, and direct derivation of MTFs using the whole

resolution pattern should help to improve the results. Another possible source of discrepancy is the inconsistency in measurement scales of optical properties and imaging path, both temporally and spatially. This is an inherent flaw in this approach and can only be addressed by a different measurement approach, likely involving new instrumentation not readily available short term. The turbulence measurements from the field indicate that the process follows that of Kolmogorov type power spectrum, which is the underlying assumption of SUIM and has been met.
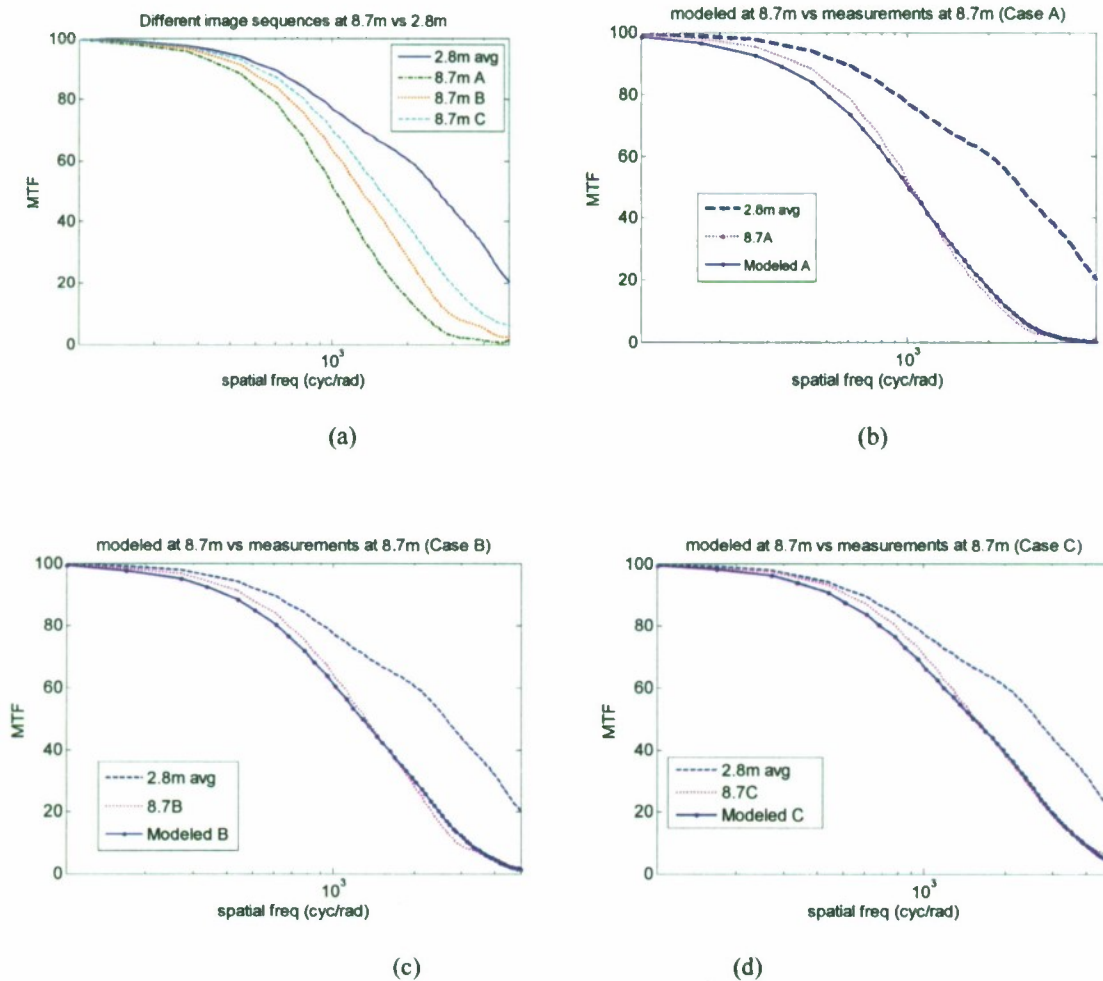


(a)

(b)

(c)

(d)

**Figure 6.** Modulation transfer functions (MTFs) estimated and modeled at different depth based on same ROI over short and long exposures for three different sequences at 8.7m, during July 27 night deployment.

The ultimate goal of understanding the level of impact of optical turbulence as well as particle scattering on image degradation is to use the knowledge to quantitatively predict the degradation, but more importantly, to restore and enhance the imaging outcome. Due to the level of degradation and distortion involved, new algorithms are being developed and details can be found in a companion paper in this volume [18]. Briefly, this approach represents synthesis of "lucky-region" fusion and optical flow based image warping. The newly developed multi-frame image restoration algorithm is applied to the sets of images collected during SOTEX, as shown in Fig. 3b. The sample results are shown in Figure 7. One can notice the enhancement over long exposure (7b), especially that around the

edges, and high spatial frequency patterns. Deconvolution with the help of known particle scattering functions is under investigation, which should further augment the level of details restored.
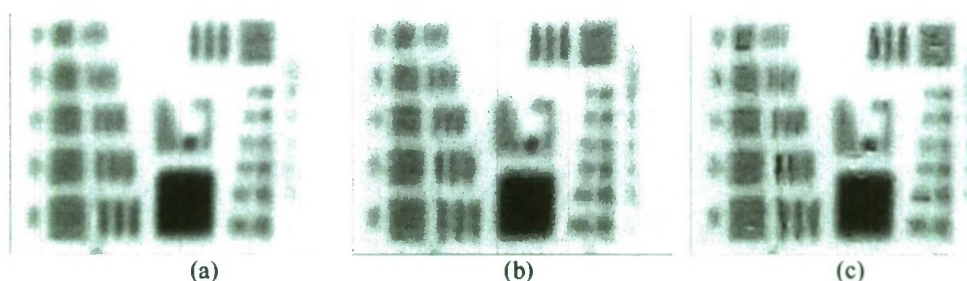


**Figure 7.** Sample image from July 27 night deployment (left, a), its long exposure sequence (middle, b) and the restored version (right, c) using optical flow and lucky patch fusion technique.

## 4. SUMMARY

To assess the level of image degradation in natural environments by optical turbulence, a rigid imaging structure, IMAST, has been built and deployed by researchers at the U.S. Naval Research Lab during SOTEX in July of 2010. Measurement results from the imaging system and turbulence probes confirmed the previously developed SUIM model as a valid tool in estimation of image degradation, based on the Kolmogorov-type power spectrum assumption. Initial attempt of restoration based on the optical flow approach fused with the lucky patch method shows promising results. Improvements on turbulence measurements and restoration efforts are under investigation. New field efforts have been completed recently and more supporting evidence can be shown in the near future.

## ACKNOWLEDGEMENT

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